

Reliability-Centric Review of Fault-Tolerant Control Systems in Power Electronics Applications

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ABSTRACT

The reliability of power electronics systems is crucial for the stable operation of modern technological infrastructures like renewable energy systems, electric vehicles, and smart grids. However, these systems are increasingly vulnerable to faults like semiconductor failures, sensor errors, and actuator malfunctions, which can degrade performance or cause system breakdowns. Fault-tolerant control (FTC) strategies have emerged as a solution to enhance the resilience and operational continuity of power electronics applications. This paper reviews FTC techniques, categorizing them into passive and active methods, and discusses their relevance to different power electronic architectures. It also examines real-world case studies in DC-DC converters, motor drives, and photovoltaic inverter systems. The review also identifies current challenges, such as computational complexity and fault detection latency, and explores emerging solutions like AI-based fault diagnosis and predictive maintenance.

Keywords: Fault-Tolerant Control (FTC), Power Electronics Reliability, Fault Diagnosis, Passive and Active Fault-Tolerant Systems, Predictive Maintenance, Intelligent Control Systems.

I. INTRODUCTION

Power electronics systems are crucial in modern technologies like renewable energy integration, electric vehicles, industrial automation, and aerospace. Their reliability is essential for infrastructure stability and efficiency. However, their intensive operating conditions, including high temperatures, switching frequencies, and electrical stresses, make them susceptible to faults like semiconductor device failures, sensor degradations, controller malfunctions, and interconnection issues. (Zhang et al., 2020).

Faults can lead to system performance degradation, catastrophic failures, increased

maintenance costs, and reduced lifespan if not managed properly. Fault-Tolerant Control (FTC) is a critical strategy to maintain system operation in the presence of faults. (Peng et al., 2021). FTC techniques are designed to detect faults promptly, isolate the faulty components, and reconfigure the control law or system operation to ensure continued service with minimal performance loss.

Broadly, FTC strategies are categorized into **passive** and **active** approaches. Passive FTC methods are designed to be inherently robust to a predefined set of faults without modifying the control structure during operation. In contrast, active FTC systems dynamically detect and accommodate faults by adjusting the control algorithm or system configuration in real-time (Morcillo et al., 2019).

In the past few years, research in FTC for power electronics has expanded rapidly, spurred by advances in artificial intelligence (AI), machine learning (ML), and real-time diagnostics. Intelligent and data-driven FTC approaches are now being explored to predict faults before they occur and optimize system reconfiguration with minimal human intervention (Xu & Wang, 2022).

II. FAULT TYPES AND FAILURE MECHANISMS IN POWER ELECTRONICS

Power electronic converters and systems operate under demanding electrical, thermal, and environmental conditions. These stresses make them vulnerable to various faults, which can impair functionality or cause permanent damage if not properly addressed. Understanding these fault types and their underlying mechanisms is crucial for developing effective Fault-Tolerant Control (FTC) strategies (Yang et al., 2019).

Common Fault Types

1. **Switching Device Faults:**Power semiconductors like IGBTs, MOSFETs, and diodes are prone to short-circuit or open-circuit faults due to electrical overstress, thermal cycling, or degradation over time (Alfi et al., 2021).
2. **Passive Component Failures:**Inductors, capacitors, and transformers experience faults such as insulation breakdown, capacitance loss, or magnetic saturation, primarily due to aging, high ripple currents, or temperature excursions (Patil et al., 2020).
3. **Sensor and Measurement Faults:**Current, voltage, and temperature sensors can provide incorrect readings due to drift, bias, or complete failure, leading to improper control actions and potential instability (Singh & Jain, 2021).
4. **Controller and Software Faults:**Errors in the digital control hardware or software algorithms can introduce wrong control signals, thereby affecting system reliability (Zhang et al., 2020).
5. **Interconnection and Communication Faults:**Faults in busbars, cables, and connectors, or failures in communication interfaces like CAN or Ethernet, can lead to partial or total system shutdowns (Xu & Wang, 2022).

Impact on System Reliability

Faults in power electronics systems can have cascading consequences. A single undetected switch fault, for example, can trigger thermal runaway, damage adjacent modules, and even cause fires in critical applications like grid-tied inverters or electric vehicles (Alfi et al., 2021). Thus, fast and accurate fault detection, isolation, and control reconfiguration are not just desirable but essential for mission-critical power electronics applications.

III. COMMON FAULT TYPES IN POWER ELECTRONICS SYSTEMS

Power electronics systems are exposed to extreme electrical, thermal, and mechanical stresses, making them susceptible to various fault types. Early identification and mitigation of these faults are essential to ensuring system reliability, safety, and longevity (Yang et al., 2019; Rahimi et al., 2021). This section discusses major fault types typically encountered.

1. Switch-Related Faults

Switching devices such as Insulated Gate Bipolar Transistors (IGBTs), Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs), and Silicon Carbide (SiC) devices are critical for power conversion. However, they are among the most failure-prone components.

- **Open-Circuit Faults:**Occur due to bond wire lift-off, die cracking, or solder joint fatigue. It leads to uneven current sharing in multi-switch systems, increasing thermal stress on healthy devices. Thereby, reducing overall system performance, often manifesting as voltage spikes or incomplete commutation (Zhao et al., 2022).
- **Short-Circuit Faults:**Result from device latch-up, insulation breakdown, cosmic ray strikes, or manufacturing defects. It Generate high fault currents within microseconds, potentially causing explosion or fire if protection is delayed (Park et al., 2023). Short-circuit detection and fast disconnection (within 10 μ s) are now standard in modern designs to minimize cascading failures (Li et al., 2021).

2. Passive Component Faults

Passive components like capacitors, inductors, and transformers play vital roles but are not immune to aging and environmental stress.

- **Capacitor Faults:**Especially Aluminum Electrolytic Capacitors degrade due to electrolyte evaporation and dielectric breakdown. Common failure indicators: Increased Equivalent Series Resistance (ESR) and capacitance drop, leading to DC-link instability or oscillations (Khan et al., 2020).
- **Inductor and Transformer Faults:**Winding degradation as a result of failed insulation as well as electromagnetic noise and efficiency loss result from core saturation at high currents (Alavi et al., 2022). Predictive maintenance based on ESR monitoring is becoming more popular for managing capacitor health.

3. Sensing and Measurement Faults

Reliable sensing is critical for feedback-controlled systems, especially in MPPT, inverters, and motor drives.

- **Sensor Hard Faults:**Complete loss of measurement due to sensor breakage, wiring faults, or interface failure.
- **Sensor Soft Faults:**Degradation in accuracy over time. As well as offset drift, noise amplification, or response delay. Redundancy and software-based sensor validation

algorithms are increasingly adopted to mitigate sensor unreliability (Gao & Zhang, 2019; Li et al., 2023).

4. Control System Faults

Control systems, including DSPs, microcontrollers, and FPGAs, are vulnerable to:

- **Bit-flips** from radiation or EMI.
- **Overheating** due to high computational loads without sufficient cooling.
- **Software Bugs** leading to unexpected system behavior (Sun et al., 2021).

5. Thermal Faults

Thermal faults are both primary and secondary causes of failure in power electronics. Thermal cycling induces solder joint fatigue, die attachment degradation, and bond wire lift-off. Over-temperature stress accelerates material aging and semiconductor parameter shifts. Junction temperatures exceeding 125°C in silicon devices or 175°C in SiC devices critically increase the probability of failure (Chen et al., 2022). Thermal faults are mitigated by deployment of active thermal management systems (fan speed modulation, liquid cooling). Embedding thermal sensors within modules for real-time junction temperature estimation (Al-Mashhadani et al., 2024).

IV. FAULT-TOLERANT CONTROL (FTC) STRATEGIES IN POWER ELECTRONICS

Fault-Tolerant Control (FTC) strategies are crucial for enhancing power electronics system reliability, especially in safety-critical applications. They are categorized into passive and active fault tolerance, each with unique features and trade-offs.

Passive Fault-Tolerant Control (PFTC)

Passive Fault-Tolerant Control (PFTC) is a system design that incorporates built-in fault tolerance without relying on fault detection and diagnosis, maintaining operation through hardware redundancy or robust control mechanisms.

- **Robust Controller Design:** Passive FTC systems use a controlled algorithm that considers potential faults, ensuring acceptable system parameters even with small faults, allowing for tolerance of variations in system parameters without significant performance degradation. (Ahmed et al., 2022). This design provides a safety buffer, ensuring the system remains operational.

- **Hardware Redundancy:** Many passive FTC systems rely on redundant components to maintain functionality during a fault. For example, redundant power converters or backup circuits are deployed to compensate for a failed unit, ensuring that the system continues to operate at reduced performance (Nambiar et al., 2021). This strategy is common in mission-critical systems like aerospace or power grid infrastructures.
- **De-rated Operation:** After a fault occurs, passive FTC systems may operate in a de-rated state, where the performance is intentionally reduced to accommodate the failure. This approach helps avoid complete shutdown, allowing for continued operation, albeit at a lower level of performance. The system's ability to "limp" along ensures some degree of service continuity, which is essential in applications requiring high availability (Li & Wang, 2023).

Active Fault-Tolerant Control (AFTC)

Active Fault-Tolerant Control (AFTC) systems are designed to detect faults in real-time, diagnose the fault type, and implement corrective actions such as switching control strategies or system reconfiguration. These systems enable more dynamic responses to faults, enhancing overall system resilience.

- **Fault Detection and Diagnosis (FDD):** In AFTC systems, real-time monitoring of critical system variables like current, voltage, and temperature is used to detect faults. These systems rely on algorithms that analyze the sensor data to quickly identify abnormal behaviors, such as current imbalances or voltage dips, which may indicate a fault (Zhou et al., 2021). The ability to detect faults early reduces the risk of catastrophic failure.
- **Reconfigurable Control Algorithms:** Once a fault is detected, AFTC systems activate algorithms that can reconfigure the system's control parameters to accommodate the fault. This may involve switching to a backup converter, adjusting the operating point of the system, or altering the energy distribution strategy to maintain operation (Kim et al., 2022). The system can thus continue to function at a lower but acceptable level of performance.
- **Dynamic Redundancy Management:** AFTC systems often incorporate dynamic redundancy management, where additional components or backup subsystems are activated in response to

specific faults. For instance, in multilevel converter systems, redundant submodules are brought online when a failure occurs, ensuring continued operation without system shutdown (Sun et al., 2021). This capability makes the system highly adaptable to various fault scenarios.

Hybrid Fault-Tolerant Control

Hybrid Fault-Tolerant Control systems combine elements of both passive and active strategies to create a more flexible and efficient fault-tolerant design. These systems seek to balance the simplicity of passive methods with the dynamic capabilities of active methods to achieve a robust yet efficient system.

- **Minor Fault Handling with Passive Methods:** For minor faults that do not significantly affect the system's performance, hybrid FTC systems rely on passive strategies. These faults are tolerated without activating complex fault detection algorithms, maintaining system simplicity and minimizing computational overhead (Tang et al., 2023).
- **Active Fault Handling for Major Failures:** For more severe or complex faults, hybrid systems can switch to active strategies. This might involve diagnostic algorithms and system reconfiguration to restore operation and minimize damage (Rahman et al., 2024). The ability to dynamically choose between passive or active responses allows the system to optimize both reliability and performance.
- **Adaptability and Efficiency:** Hybrid FTC systems are particularly beneficial for large-scale and distributed power electronics systems where fault conditions can vary significantly. By offering the flexibility to adapt to different types of faults, these systems can achieve high reliability and fault tolerance with relatively lower complexity than fully active systems (Zhou et al., 2021).

Emerging Trends in FTC for Power Electronics

The landscape of FTC is rapidly evolving, with new technologies and methodologies offering even greater reliability and fault tolerance in power electronics systems. These emerging trends reflect the growing need for fault-tolerant designs in complex and high-demand applications.

- **AI-based Diagnosis:** Machine learning and artificial intelligence (AI) are being integrated into FTC systems for faster and more accurate fault detection. AI algorithms can analyze large sets of sensor data to identify faults that

would be difficult for traditional algorithms to detect. This technology is expected to improve fault detection speed and accuracy, thereby reducing system downtime (Lu et al., 2022).

- **Sensorless Fault Detection:** In many power electronics systems, sensors are used to monitor critical parameters such as current and voltage. However, reliance on sensors can be a limitation, especially in harsh environments where sensors may fail. Sensorless fault detection techniques use estimation algorithms to infer system states without relying on physical sensors, enhancing system robustness and reducing maintenance costs (Kim et al., 2021).
- **Distributed FTC:** In modular or distributed power systems, local controllers work together to manage faults and optimize system operation. Distributed FTC allows for more efficient use of system resources by enabling each controller to manage its own fault tolerance strategies. This approach is particularly useful in microgrids and large-scale power systems where central control may be difficult (Rahman et al., 2024).

V. RELIABILITY ASSESSMENT METRICS FOR FAULT-TOLERANT POWER ELECTRONICS SYSTEMS

Reliability assessment is critical for evaluating the effectiveness of fault-tolerant control strategies in power electronics applications. It provides quantifiable insights into how systems perform under fault conditions and over their operational lifetime. In this section, we review key metrics and evaluation approaches that are widely adopted in reliability analysis.

Mean Time Between Failures (MTBF): MTBF is a crucial indicator of system reliability, particularly in mission-critical applications (Yang et al., 2022). It measures the average time a system operates before failure, indicating a system's likelihood of minimizing downtime. In power electronics with FTC, MTBF helps quantify fault mitigation strategies' effectiveness in extending operational periods without failure. However, MTBF calculations assume constant failure rates, which may not be applicable under varying thermal and electrical stresses, necessitating the use of dynamic reliability models (Luo & Xie, 2021).

Fault Detection Rate (FDR): Fault Detection Rate (FDR) is a crucial measure of a system's ability to detect and mitigate faults, indicating its robustness. A high FDR is essential for active fault-tolerant

strategies, reducing unexpected failures, performance degradation, and repair costs. FDR can be evaluated through accelerated life testing, fault injection experiments, or simulation studies, where known faults are intentionally introduced. (Zhou et al., 2021)

Fault Recovery Time: Fault Recovery Time is the time between fault detection and successful system reconfiguration or restoration, ensuring system stability and minimizing downtime in critical applications like aerospace or industrial drives. In high-speed power converters, short recovery times prevent cascading failures (Sun et al., 2021). Advanced reconfigurable control strategies, like predictive control or adaptive algorithms, significantly reduce recovery times. (Kim et al., 2022).

Fault Coverage Ratio: Fault Coverage Ratio measures the proportion of all possible faults that the FTC system can effectively detect and handle. It is a broader metric than Fault Detection Rate, encompassing both detection and successful response. A high coverage ratio is essential for systems deployed in hostile environments, such as offshore wind farms or spacecraft, where maintenance is infrequent and costly (Tang et al., 2023). Achieving high fault coverage often requires a trade-off with system complexity and cost. Including mechanisms for very rare fault types can substantially increase system design overhead.

System Availability: Availability is defined as the ratio of uptime to the total time (uptime + downtime). It combines both reliability and maintainability into a single figure, usually expressed as a percentage (e.g., "five nines" or 99.999% availability). High availability is often the primary goal for critical power electronics systems. FTC systems contribute to higher availability by minimizing the impact of faults through quick detection and response (Rahman et al., 2024). Component redundancy, fault detection accuracy, and recovery speed are major factors influencing availability. Improvements in any of these areas can lead to substantial gains in overall system performance.

Lifetime Prediction Models: Lifetime prediction models estimate how long a system or its components will operate before failure, based on stress factors like thermal cycling, electrical load, and mechanical vibration. Reliable lifetime predictions allow engineers to design maintenance schedules and predict warranty periods more accurately. FTC strategies can be integrated into lifetime models to assess how fault mitigation extends component life (Lu et al., 2022). Methods

such as Rainflow counting for stress cycles, Miner's rule for cumulative fatigue, and physics-of-failure models are commonly used in the lifetime estimation of power electronics.

Fault Tolerance Index (FTI): The Fault Tolerance Index quantifies the system's ability to continue operating normally or with minimal performance degradation under fault conditions. FTI provides a normalized way to compare different FTC architectures across various types of faults and applications. Higher FTI values indicate better system resilience (Zhou et al., 2021). FTI is often based on a weighted sum of several sub-metrics like fault coverage, recovery time, and performance degradation, offering a holistic view of system robustness.

VI. CONCLUSION

Fault-tolerant control (FTC) in power electronics has become a critical discipline due to the growing demand for reliable and resilient energy systems. The focus has shifted from basic hardware redundancy to intelligent control and diagnostic approaches, aiming to achieve dynamic system reliability without excessive cost or complexity. Key methods include active fault detection, hardware reconfiguration, control re-design, and predictive maintenance. However, emerging challenges like complexity in multilevel systems, real-time diagnosis requirements, and cybersecurity threats require a holistic, interdisciplinary approach. Future progress will involve embracing artificial intelligence, developing self-healing systems, and advancing standardization for safety-critical applications. As the global transition to electrification accelerates, designing power electronic converters and controllers with intrinsic fault tolerance will become a necessity, shaping the next generation of sustainable and resilient electrical energy infrastructures.

REFERENCES

- [1]. Ahmed, M., Lee, C., & Kumar, P. (2022). Robust control design for fault-tolerant operation of power electronic systems. *IEEE Transactions on Power Electronics*, 37(8), 6503–6515.
- [2]. Alavi, H., Moazami, N., & Ortega, R. (2022). Condition monitoring of inductors and transformers in power electronics using electromagnetic and thermal signatures. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 10(1), 350–361.

- [3]. Alfi, A., Zhang, B., & Li, W. (2021). Failure analysis of power semiconductors under thermal stress conditions. *Microelectronics Reliability*, 121, 114117.
- [4]. Al-Mashhadani, F., Yusuf, M., & Choi, D. (2024). Real-time thermal monitoring for SiC power modules using embedded sensors. *IEEE Transactions on Industrial Electronics*, 71(2), 1286–1295.
- [5]. Chen, H., Yu, L., & Zhao, Y. (2022). Thermal failure mechanisms and reliability modeling in power electronic modules. *IEEE Transactions on Device and Materials Reliability*, 22(3), 211–219.
- [6]. Gao, L., & Zhang, Q. (2019). Sensor fault detection and diagnosis in photovoltaic systems using statistical redundancy. *Renewable Energy*, 132, 1027–1037.
- [7]. Khan, M. H., Chen, F., & Du, Y. (2020). Health prognosis of aluminum electrolytic capacitors in DC-link applications. *IEEE Transactions on Power Electronics*, 35(9), 9372–9382.
- [8]. Kim, H., Zhao, T., & Choi, Y. (2021). Sensorless fault detection using model-based estimation in power electronics. *IEEE Transactions on Industrial Informatics*, 17(4), 2954–2962.
- [9]. Kim, S., Park, J., & Lee, H. (2022). Reconfigurable control techniques for fault-tolerant converters using adaptive model predictive control. *IEEE Transactions on Power Electronics*, 37(11), 12354–12364.
- [10]. Li, J., & Wang, Y. (2023). Degraded operation strategies for fault-tolerant power inverters with component failure. *Energies*, 16(1), 45.
- [11]. Li, X., Chen, Z., & Kumar, R. (2021). Fast short-circuit protection techniques for IGBT-based converters. *IEEE Transactions on Power Electronics*, 36(10), 11207–11217.
- [12]. Li, Y., Gao, S., & Wang, T. (2023). Redundancy-based fault management in sensor networks for electric drive systems. *Sensors*, 23(4), 1023.
- [13]. Luo, Q., & Xie, D. (2021). Dynamic MTBF modeling in thermally stressed power electronics systems. *Microelectronics Reliability*, 122, 114305.
- [14]. Lu, Y., Tan, C., & Sun, J. (2022). AI-based prognostics for lifetime estimation in power converters. *IEEE Transactions on Industrial Electronics*, 69(9), 9012–9023.
- [15]. Morcillo, A., Vidal, M., & Ortega, J. (2019). A comparative study of active and passive fault-tolerant control systems in aerospace applications. *Aerospace Science and Technology*, 92, 214–224.
- [16]. Nambiar, R., Singh, V., & Kumar, S. (2021). Hardware redundancy strategies for mission-critical power electronics. *International Journal of Electrical Power & Energy Systems*, 133, 107261.
- [17]. Park, S., Jang, M., & Lee, C. (2023). Mechanisms and mitigation of short-circuit faults in SiC MOSFETs. *IEEE Transactions on Industrial Electronics*, 70(3), 2455–2466.
- [18]. Patil, V., Tripathi, A., & Deshmukh, S. (2020). Failure analysis of magnetic components under high-frequency switching conditions. *Journal of Power Electronics*, 20(5), 1278–1289.
- [19]. Peng, X., Wei, J., & Wang, X. (2021). Survey on fault-tolerant control techniques in power electronics and motor drives. *IEEE Access*, 9, 115344–115364.
- [20]. Rahimi, A., Alizadeh, H., & Rezaei, A. (2021). Review of fault detection and tolerance in DC-DC converters. *IEEE Transactions on Industrial Applications*, 57(5), 5022–5034.
- [21]. Rahman, S., Ali, M., & Khan, J. (2024). Hybrid FTC strategies in modular power converters: Design and implementation. *Electric Power Systems Research*, 235, 108074.
- [22]. Singh, R., & Jain, V. (2021). Sensor faults and calibration errors in closed-loop control of power converters. *IEEE Sensors Journal*, 21(6), 7103–7112.
- [23]. Sun, Y., Zhang, W., & Liu, X. (2021). Redundant control architecture for fault-tolerant multilevel converters. *IET Power Electronics*, 14(9), 1794–1804.
- [24]. Tang, Z., Zhang, M., & Qiao, W. (2023). Fault detection coverage and risk analysis in distributed power systems. *IEEE Transactions on Smart Grid*, 14(2), 1129–1138.
- [25]. Xu, L., & Wang, P. (2022). AI-based fault detection in smart inverter systems: Techniques and trends. *IEEE Transactions on Industrial Informatics*, 18(1), 122–131.
- [26]. Yang, B., Liu, J., & Tan, Y. (2019). Overview of failure modes in power

- electronic converters. *Journal of Power Electronics*, 19(6), 1536–1546.
- [27]. Yang, H., Chen, L., & Zhou, Z. (2022). Reliability metrics and MTBF evaluation in renewable energy converters. *Renewable and Sustainable Energy Reviews*, 153, 111789.
- [28]. Zhang, F., Liu, K., & Wang, J. (2020). Challenges in reliable operation of power electronic systems and fault-tolerant control approaches. *IEEE Transactions on Industrial Electronics*, 67(8), 6683–6693.
- [29]. Zhao, Y., Chen, H., & Zhou, Q. (2022). Open-circuit fault diagnosis in IGBT-based converters using real-time current signature analysis. *IEEE Transactions on Power Electronics*, 37(3), 3412–3422.
- [30]. Zhou, X., Wu, H., & Li, F. (2021). Active fault-tolerant control strategies for grid-connected power electronic converters. *IEEE Transactions on Industrial Applications*, 57(3), 3121–3132.